Systemic Risk and the Ripple Effect in the Supply Chain

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Abstract Supply chains are highly complex systems, and disruptions may ripple through these systems in unexpected ways, but they may also start in unexpected ways. We investigate the causes of ripple effect through the lens of systemic risk. We derive supply chain systemic risk from the finance discipline where sources of risk are found in systemic risk-taking, contagion, and amplification mechanisms. In a supply chain context, we identify three dimensions that influence systemic risk, the nature of a disruption, the structure, and dependency of the supply chain, and the decision-making. Within these three dimensions, there are several factors including correlation of risk, compounding effects, cyclical linkages, counterparty risk, herding behavior, and misaligned incentives. These factors are often invisible to decision makers, and they may operate in tandem to exacerbate ripple effect. We highlight these systemic risks, and we encourage further research to understand their nature and to mitigate their effect.

1 Introduction

There is no doubt regarding the complexity of today's supply chains. Academic literature, consulting reports, and popular press all discuss the challenges associated with handling disruption events in supply chains that span the globe. A company is only as robust as its supply chain, and risk management is becoming increasingly important as companies extend their global reach. Similarly, a survey of global firms noted that disruptions in the supply chain have a significant impact on performance

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(Levi et al. 2013). As such, understanding and managing supply chain disruptions has become a key focus for companies (Blackhurst et al. 2008).

Global supply chains are complex in many ways including the sheer number of connections, as well as the fact that total visibility within these systems is difficult. Indeed, many of the intricacies of the structure and relationships in a supply chain are often unknown or partially known at best. Moreover, supply chain complexity is increasing due to a number of reasons including the following:

- Increased dependencies amongst partners in the supply chain.
- Increased changes in supply chain design.
- Increased new product introductions coupled with increased customization of products.
- Increased number of partners in the supply chain.
- Decreased transparency in supply chain relationships (Levi et al. 2013).

Companies often have little to no visibility of supply chain design past tier 1 suppliers. In other words, a firm may know whom their direct supplier are, but they may not know the suppliers to those suppliers. Likewise, they may be unaware of the partnerships and competitive relationships that exist upstream in their supply chain. All of these factors increase the complexity of supply chains and as a result, vulnerability to disruption events interrupts the flow of goods and services.

As an example of a disruption hitting a supply chain, many reports note the Japanese earthquake in 2011, the largest earthquake to hit Japan in 1500 years of recorded history (Sheffi 2015). Reports track the impacts of the earthquake on companies such as Nissan (Levi et al. 2013) and Intel (Sheffi 2015). Other well-known disruptions include floods in Thailand or Hurricane Sandy in the United States in 2012 (Bhatia et al. 2013). These high-impact disruptions are well known as they affect many companies in a supply chain. In addition, the impact of the disruption propagates to other areas and partners in a supply chain. This propagation is termed the "ripple effect" of the disruption in the supply chain (Ivanov et al. 2014).

These "low probability/high impact" events such as the 2011 Japanese earthquake are considered to be a primary cause of ripple effect (Ivanov et al. 2014). However, we contend that also seemingly small disruptions can grow and propagate throughout the supply chain with devastating impacts. These disruptions may not make popular press outlets, but the effects can still be large and impactful. In addition, unlike low probability events, many "high probability/low impact events" are actually much larger than ever anticipated. One such example is demonstrated in a recent conversation with a manager at a global aerospace firm headquartered in the United States. The discussion centered around dynamically managing safety stock in real time and in response to current events in the supply chain. While low probability/high-impact events were discussed, it was also noted that the everyday glitches (or high probability/low-impact events) in the supply chain can have a significant and negative impact. A recent shortage of screws costing less than $100.00 USD each cost the company over $2 million USD in lost sales. In this example, a seemingly small disruption rippled out from a point of origin to other parts of the supply chain with noticeably growing impact.

In this chapter, we expand on the concept of ripple effect and focus on potential causes through the lens of systemic risk. Specifically, we identify each of the three dimensions of systemic risk: (1) the nature of a disruption, (2) the structure and dependency within the supply chain, and (3) the decision-making of supply chain managers. Within these dimensions, we discuss six factors: (1) correlation of risk, (2) compounding effects, (3) cyclical linkages, (4) counterparty risk, (5) herding behavior, and (6) misaligned incentives that influence the ripple effect. We first describe ripple effect. Next, we discuss the origin of systemic risk in the world of finance. This is followed by defining supply chain systemic risk, its dimensions, and factors. We then describe how each factor can influence ripple effect. Finally, we discuss implications for managers and call for more research in this area.

2 Ripple Effect

Ripple effects have been discussed in many different disciplines and share the similar characteristic of the continued propagation of an effect within a system. For example, it has been shown that moods can be passed among members of a group in a form of emotional contagion (Barsade 2002). Customer loyalty is also contagious with happy customers making new customers by sharing their positive experiences through word of mouth (Gremler and Brown 1999). The price of houses is influenced by other house prices (Meen 1999). The happiness a pet brings to its owner will extend to non-pet owners and beyond (Wood et al. 2007). When an error is introduced in software development, the effect will cascade throughout the code well beyond the originating module (Black 2001, 2006; Haney 1972; Yau et al. 1978).

Within the context of the supply chain, Ivanov, Sokolov, and Dolgui define the ripple effect as "the impact of a disruption on the SC performance and disruption-based scope of changes in the SC structures and parameters" (Ivanov et al. 2014). It is also known as the domino effect (Dolgui et al. 2018). Dolgui et al. (2018) differentiate between ripple effect and bullwhip effect in terms of frequency and severity of disruptions. They contend that a ripple effect occurs with low frequency and high intensity, while the bullwhip effect has a higher frequency and lower severity. The ripple effect has also been described by Hearnshaw and Wilson (2013) in terms of cascading failures in the supply chain.

However, as laid out in the introduction, we believe that the bullwhip effect is one type of ripple effect, and that frequency and intensity are not distinctions of the two. In fact, we argue that it is possible for small disruptions to gain intensity and become very problematic based on how the supply chain system responds. It is due to the highly connected and interdependent nature of relationships in the supply chain that create this environment. Because the dependence of one partner on another may be large, there is a systemic nature to supply chain risk where a disruption can occur not only at one specific point in the supply chain but ripple, extend, and intensify to other parts of the supply chain.

Moreover, the lack of visibility into the depths of the supply chain as well as the fact that a company's partners may be part of other, unknown supply chains can create higher levels of risk not previously studied. We discuss the impact of systemic risk on ripple effect of disruption events in the supply chain.

3 Systemic Risk

The concept of systemic risk comes from finance and economics, and there is a growing body of literature investigating the causes and effects of systemic risk in the finance literature. In fact, Basole and Bellamy (2014) study risk diffusion in supplier networks and note the finance literature for insights in studying the propagation of risks such as contagion stemming from shocks in financial networks and the impact of different forms of systemic risk on financial stability.

Systemic risk is "the risk or probability of breakdowns in an entire system, as opposed to breakdowns in individual parts or components, and is evidenced by co-movements (correlation) among most or all the parts" (Kaufman and Scott 2003). Similarly, Acharya (2009) discusses systemic risk where one bank's failure propagates as a contagion causing the failure of many banks in the financial system. Agca et al. (2017) note that supply chains are a mechanism through which disruptions (in the context of financial shocks) can spread. In this regard, the intersection of systemic risk and supply chains is interesting and timely.

In their survey of financial systemic risk literature, Benoit et al. (2017) group research by the sources of systemic risk. The three groups are:

1. Systemic risk-taking—why financial institutions take risks that are large and connected or correlated.
2. Contagion mechanisms—how losses spill over from one part of a financial system to another.
3. Amplification mechanisms—why small disruptions or shocks can have much larger impacts.

The concept of systemic risk is likened to understanding the fragility of a network—consideration of where the system is susceptible to the ripple effect of a disruption. We use systemic risk as a lens though which to examine and understand supply chain risk and the ripple effect of a disruption.

3.1 Dimensions of Supply Chain Systemic Risk

Scheibe and Blackhurst (2018) link systemic risk to supply chain ripple effect through a qualitative study investigating 21 companies in 7 supply chains, at 3 levels each. In this research, 3 aggregate dimensions of systemic risk factors that influence the ripple effect emerged:

- Nature of the disruption
- Supply chain structure and dependence
- Managerial decision-making.

Under each of the three dimensions are systemic risk themes. First, under the dimension of understanding the nature of the disruption, we discuss the conception of correlation of risk and the compounding effects of a disruption as it ripples through the supply chain. Next, under the dimension of the structure of the supply chain and the dependence within that structure, we discuss the interesting phenomenon of cyclical linkages (a type of structure that impacts the ripple effect) and counterparty risk (hidden relationships and dependency that increase risk exposure). Finally, under the dimension of managerial decision-making in the supply chain, we discuss herding behaviors and the influence of misaligned incentives.

3.1.1 Nature of Disruption

The first of the three aggregated dimensions is the nature of the disruption itself. Disruptions will vary in frequency and severity, and the disruptions themselves have characteristics that will influence the way in which they will ripple through a system. Specifically, disruptions are influenced by the correlation of risks and the way in which some types of disruptions have a compounding effect.

Correlation of Risk

When Chopra and Sodhi (2004) described different risk mitigation strategies, they depicted how it would be possible to reduce some risks and increase others. For example, a company could add inventory and that would have a small reduction of risk in disruptions, a greater reduction in delay risk, a small reduction in procurement risk and capacity risk, but would increase inventory risk. This is shown in Table 1 and is an excellent example of the correlation of risk events in a supply chain. Risks cannot be considered in isolation, and supply chain managers must understand the related nature of the risks, or they may inadvertently cause a disruption while trying to mitigate the risk of a disruption in another area.

Ackermann et al. (2007) notes that it is the *interaction* of risks that can cause the most damage. Therefore, the managers must consider more than just individual risks themselves. In fact, one risk can reinforce the likelihood of another risk occurring. The managers should be continually looking for and understanding these interactions by employing the functional expertise of many within the company. In other words, managing the ripple effect in the supply chain should span beyond functional boundaries.

Moreover, the managers should look to new technologies and the use of analytics to understand risk correlations. For example, Sheffi (2015, p. 207) notes the emergence of firms like Verisk Analytics who “use data science to find possible

Table 1 Mitigation strategies from Chopra and Sodhi (2004)

Mitigation Strategy	Disruptions	Delays	Forecast risk	Procurement risk	Receivables risk	Capacity risk	Inventory risk
Add capacity		↓		▼		↑	▼
Add inventory	▼	↓		▼		▼	↑
Have redundant suppliers	↓			▼		▲	▼
Increase responsiveness		↓	↓				
Increase flexibility		▼		▼		↓	▼
Aggregate or pool demand			↓			↓	↓
Increase capability		▼					▼
Have more customer accounts					▼		

Greatly Increase Risk ↑ ▼ Decrease Risk

Increase Risk ▲ ↓ Greatly Decrease Risk

correlations between various incidents and impending geopolitical events that may disrupt businesses." Many firms are creating and enhancing in-house systems leveraging analytics.

Compounding Effects

The compounding effect of risk is similar to the concept of flutter in the physical sciences. A classic example of flutter is the "Galloping Gertie" (Kambhu et al. 2007) where the Tacoma Narrows Bridge, a suspension bridge spanning a part of the Puget Sound in Washington, was subjected to strong winds and began to twist and vibrate until it collapsed into the water. By itself, the wind was not enough to destroy the bridge, but as the bridge oscillated, the vibrations fed on themselves and worsened. This cyclical compounding effect, in combination with shock and contagion, is in great part responsible to the collapse of the stock market and the resulting Great Depression.

The bullwhip effect is a classic example of the compounding nature of disruptions (Fig. 1). Small variations in demand can grow in intensity up the supply chain, particularly when there is information lag. Another contribution to the compounding nature of disruptions is the decisions made by actors in the supply chain. This is

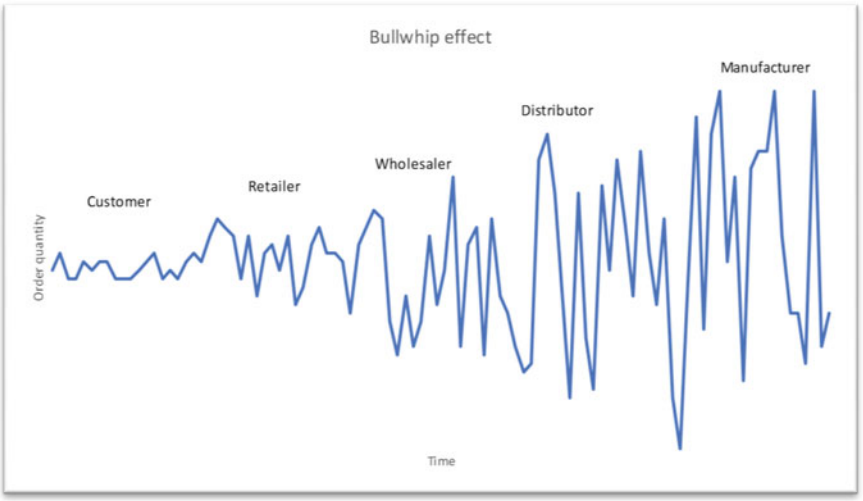

Fig. 1 Bullwhip effect

especially true when the decisions are self-preserving and potentially at the cost of the other actors. When decision makers engage in protectionist or even opportunist type decisions, the disruption may grow as it is passed onto supply chain partners and suppliers. A company may decide to increase inventory to withstand a particular disruption but by doing so, they encourage ripple effect.

We encourage managers to monitor and understand the impact of these compounding effects where a seemingly minor disruption can cause massive damage. Sheffi (2015, p. 161) notes that while firms have visibility of tier 1 partners, there is little visibility into "deep-tier" supply chain partners and warn of "the impact of a disrupted supplier ripples outward from the supplier to more distant customers."

3.1.2 Supply Chain Structure and Dependence

The second aggregate dimension in systemic risk is the structure of the supply chain and the dependencies of the partners. When supply chains are tightly coupled with high levels of dependencies, they are more susceptible to disruptions. Basole and Bellamy (2014) note that network structure influences the rate at which risk ripples through the supply network like a line of dominos (Fig. 2).

Interestingly, technology has enabled supply chain partners to become more dependent upon each other, which can increase efficiencies, but also increase the risk of ripple effect. Scheibe and Blackhurst (2018) found two factors that greatly influenced the systemic risk nature of ripple effects in supply chains, cyclical linkages, and counterparty risk.

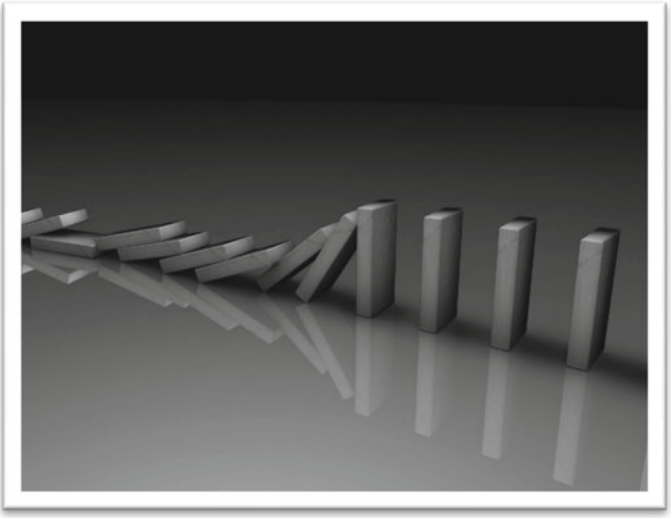

Fig. 2 Dominos

3.1.3 Cyclical Linkages

To explain cyclical linkages, let us note that it is not uncommon for final/assembled products to have subassemblies. Consider the simple example in Fig. 3 where A supplies a part to B. B then takes the part that was supplied by A and modifies it and sends it on to C, which does the same and sends it to D. D takes the subassembly, modifies it, and finally ships it to A where it may be put into final assembly. Therefore, if there is a disruption in A, the cyclical nature of this supply chain will cause A to experience the disruption not only in the first round but also in the second. If there are additional loops in subassembly modification, this problem will only increase. This possibility of structure increasing risk exposure is discussed through the lens of systemic risk by Eisenberg and Noe (2001) by looking at risk prorogation in a financial network. The same logic applies in a supply chain context, especially in industries where circular linkages are common and perhaps not readily visible.

Ackermann et al. (2007) note that circular linkages can cause vicious cycles where a risk event evolves into a self-sustaining disaster. The managers must be vigilant in understanding these structural pitfalls in their supply chains.

3.1.4 Counterparty Risk

A supplier to a company may be a supplier to a competitor or even a company in a different industry. As such, a supply chain supply partner may be a part of multiple supply chains. In financial systemic risk literature, Acharya and Engle (2009) state

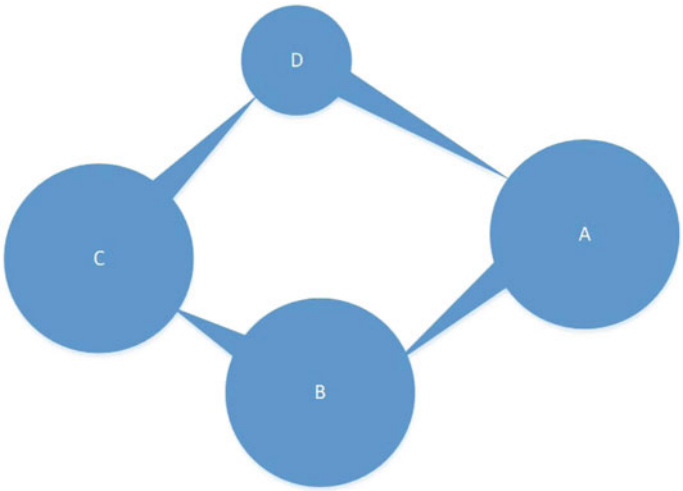

Fig. 3 Cyclical linkages

that "a party to a financial contract may sign a second, similar contract with someone else—increasing the risk that it may be unable to meet its obligations on the first contract. So, the actual risk on one deal depends on what other deals are being done." This exemplifies counterparty risk. It occurs when one partner in a supply chain is affected by the decision of other partners in hidden ways.

Consider Fig. 4. Two separate supply chains share a common partner, Company A. In supply chain 1 (SC1), a supplier to Company A experiences some kind of disruption and are not able to supply product. This will cause a disruption to ripple through SC1. However, since Company A is engaged in both SC1 and supply chain 2 (SC2), it is possible that it will need to refocus efforts to mitigate the disruption in SC1. This might be done by reallocating resources that might have been used in SC2, thus the ripple of the disruption in SC1 can also be felt in SC2 even though the actual disruption did not occur in SC2. It is unknown whether the disruption will ripple in SC2 based on the disruption in SC1. Several factors will influence the ripple. For example, if the customer of Company A in SC1 is significant, then they may be motivated to shift resources from SC2 to satisfy the needs of the customer in SC1. However, if the partners in SC2 are more important, then the ripple may never be felt in SC2 but would be exacerbated in SC1. This is almost impossible to proactively plan for this type of disruption because it is difficult enough to know one's own supply chain beyond the first tier, let alone an entirely different supply chain that may be shared by common partners. Therefore, it is important for suppliers to maintain some level of agility to be able to overcome these unforeseen disruptions.

This risk is particularly interesting as it has not been discussed in the supply chain literature. We believe that counterparty risk is a source of great and not-well-understood danger. Counterparty risk is a risk that needs to be better understood.

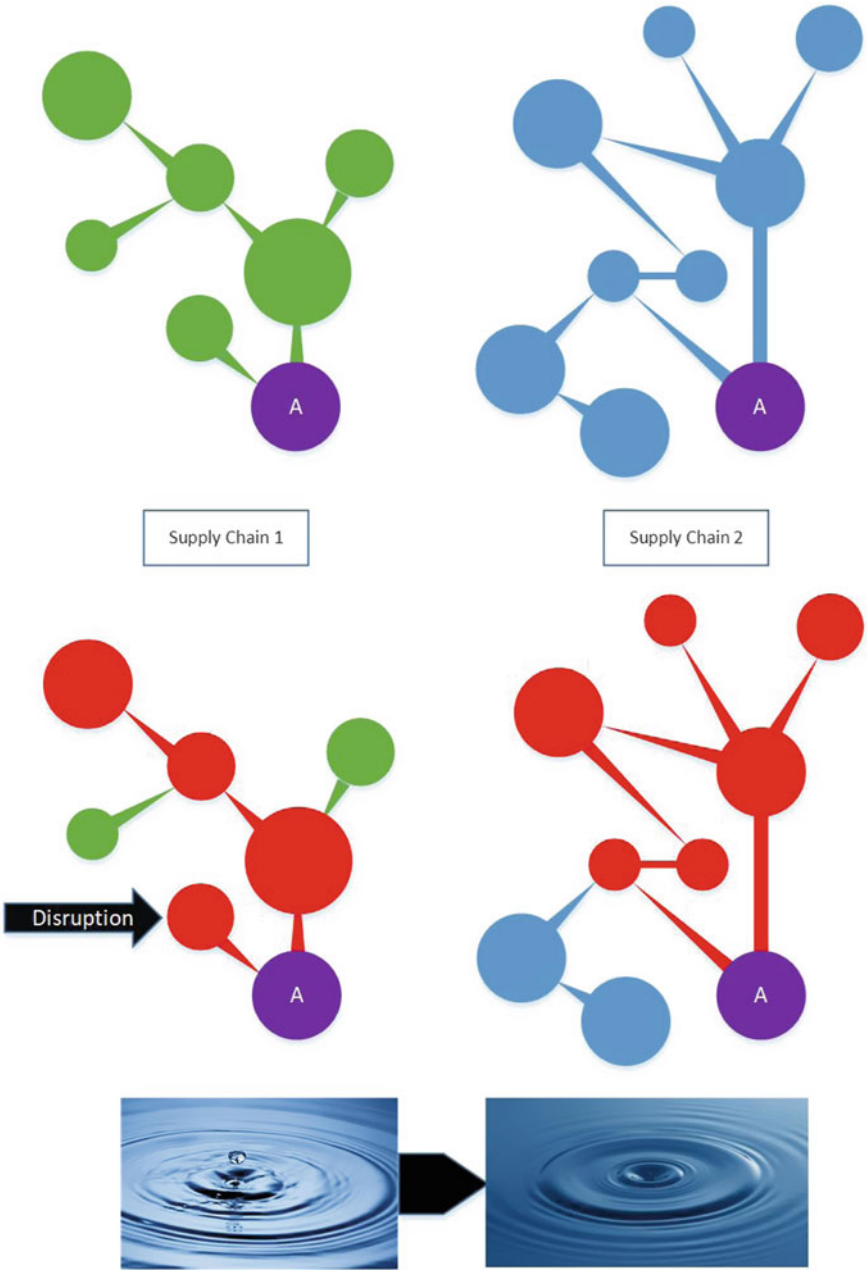

Fig. 4 Counterparty risk

However, we warn that this is much more than understanding one's own supply chain. Rather, understanding one's supply chain partners and with whom they are connected and exposed to risk. Sheffi (2015) notes that the detection of disruptions in deep-tier or hidden parts of the supply chain is essential. Again, this is a prime opportunity for supply chain analytics.

3.1.5 Managerial Decision-Making

Herding

Herding behavior (Fig. 5) occurs when firms behave in a similar fashion after a disruption occurs. The reaction to a disruption will most likely be to protect their own interests, but in doing so, they can increase the effect of the disruption. For example, when a fire occurred in a memory manufacturer in China, the prices of memory soared as suppliers all competed for the remaining stock of memory remaining in the market. As memory was purchased to increase the safety stock levels in individual companies, the entire supply chain suffered. Organizations that may not have actually needed the memory still purchased it just to be safe.

Here, the manager should understand trends and risk event worldwide to get ahead of herding disasters. Certainly, risk hedging is a part of this, but we caution the managers to think "bigger" and perhaps include these conversations in new product development initiatives or even redesign initiatives. We also wonder whether being "ahead of the curve" on herding decisions could be used as a competitive advantage in the supply chain. If a shortage on material or part is looming, could a firm purchase inventory ahead of the need? If a logistics channel is challenged, could capacity be

Fig. 5 Heard of Lamas

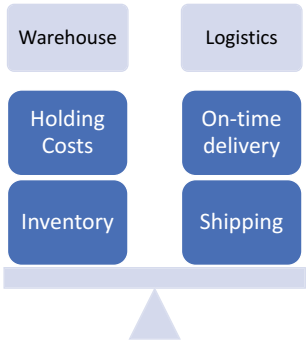

Fig. 6 Misaligned incentives

purchased in advance? Of course, that may not address the danger of herding. It would simply be an attempt to be in the front of the heard.

Misaligned Incentives

Misaligned incentives occur when individuals, groups, divisions, or organizations are rewarded for behaviors that would conflict with others within and across organizations. For example, consider a company with separate division of warehousing and logistics. If a company wants to reward keeping costs low, a conflict will exist. For a warehouse to keep costs low, a manager would want to keep the inventory levels as low as possible which would require more frequent shipping. However, for the shipping manager to keep costs low, it would be better to wait to optimally fill trucks before they left dock. Thus, cost savings from one division would come at the expense of the other. From an organizational perspective, it would be better for both warehousing and shipping to find a happy medium where both would incur greater costs, but the savings to the entire company would be higher (Fig. 6). This problem exists not only within an organization, but across organizations, and that makes it even more difficult to see, where information may not be shared (Narayanan and Raman 2004).

Managers should remember that looking at the whole system is important. While tactical or lower level incentives are critical to measure performance, do they link up to the strategic and long-term goals of the firm?

4 Discussion and Conclusions

We end this chapter with an interesting example of the ripple effect and systemic risk related to the 2011 earthquake. Sheffi (2015) studied this event from the point of view of General Motors. General Motors had estimated that 390 parts might be disrupted based on their knowledge of their supply chain and the extent of the disaster. However,

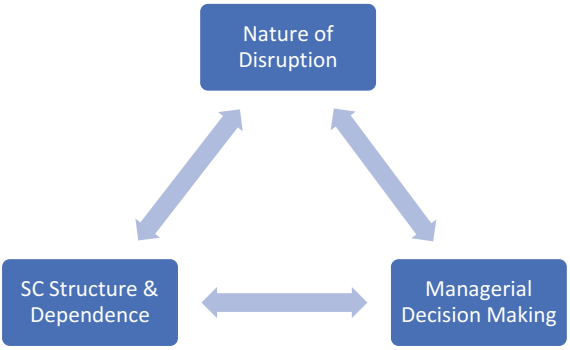

Fig. 7 Interrelated nature of systemic risk (Scheibe and Blackhurst 2018)

that estimate was greatly underestimated due to hidden impacts and relationships in the supply chain. In fact, over 6,000 parts were affected.

The challenge that systemic risk presents with ripple effect is that each of the dimensions is influential and is often unseen, but it is the combination of dimension that really drives ripples throughout a system. It is important for firms to be aware of the interconnectedness of the three dimensions and that the systemic risk themes rarely occur in isolation. The literature often discusses disruptions from a natural disaster perspective, but these disruptions may occur as a consequence of the structure of the supply chain or the choices made by managers.

Researchers are attempting to focus on the relationship between these dimensions, but given the complexity of supply chains, the hidden nature of many risks, and the unexpected interactions of these dimensions, it is common to only address one or two of the risk factors at a time. There still remains a tremendous amount of research investigating how these systemic risk factors interact, and how that affects the ripple effect, supply chain robustness, and resiliency, and how risk managers can adequately plan for and mitigate the effect of disruptions.

We present risk types along the following three interrelated dimensions: Nature of the Disruption, Structure and Dependence of the Supply Chain, and Managerial Decision Making (Fig. 7).

Nature of the Disruption:

In this dimension, we discuss the conception of correlation of risk and the compounding effects of a disruption as it ripples through the supply chain. With regards to the correlation of risk, we encourage the managers to build cross-functional teams to understand the impact of risk events on each other. For example, if a supply manager institutes a JIT policy on key inventory items to reduce the risk of obsolesce and high inventory cost, this might increase the risk of customer shortages and high expediting costs if there is a disruption in the supply chain. We also encourage the use of analytics to understand the nuances and links between risk types. With regards to the compounding effects, much attention is given to large and well-known events such as earthquakes. While it is important to manage these risks, the smaller everyday occurrences have the potential to grow and ripple through the supply chain. As

such, the managers must be ever vigilant with planning frameworks for high impact, low probability events but also the flexibility and resources for the high probability, low-impact events that can escalate is not addressed.

Structure of the Supply Chain

Modern supply chains are information driven. The world continues to increase in connectivity. Industry 4.0 is driving real-time data analysis, and this allows supply chains to become extremely efficient. However, this efficiency may come at a cost. In one respect, it is as though the dominos are being placed even closer together, so when one begins to topple, it becomes nearly impossible to prevent others from falling as well.

In this dimension, we not also discuss the structure of the supply chain but also the dependence within that structure. Here, the concepts of cyclical linkages (a type of structure that impacts the ripple effect) and counterparty risk (hidden relationships and dependency that increase risk exposure) are presented. We encourage the managers to strive to better understand the structure and links within the supply chain. From supply management frameworks and mapping exercises to more extensive deep dives into the supply chain and employing supply chain risk monitoring firms. Not only is your supply chain susceptible to disruptions from your partners and suppliers, but it could also be exposed to disruptions in entirely different supply chains. We believe that this dimension is the least understood dimension and poses the highest threat to firms. Academic research in this area is encouraged to understand and manage these risk types. We have been able to demonstrate its existence, but more research should be devoted to this effect.

Managerial Decision-making

In this dimension, we discuss herding behaviors and the impact of misaligned incentives. We encourage the managers to leverage improved decision-making for a competitive advantage and work to truly align incentives across the supply chain. The mangers ought to consider a bigger picture, but that also presents its own problems. We had several conversations with a large organization developing highly complex products. This manufacturer had 300 tier 1 suppliers, and 3000 tier 2 and above. Some of their tier 1 was also their tier 2, 3, and 4. They had no clear picture of how exposed their product was based upon disruption events. They told us that when the tsunami hit Japan, they went to their tier 1 suppliers to see if they were going to be affected. They even looked into their tier 2, and they determined they were okay, only to find they had a tier 4 supplier that was greatly affected, and this rippled through the system and did, indeed, affect the company's products.

The concept of supply chain ripple effect has grown in popularity over the last few years. Because disruption will ripple through a system, a systemic risk perspective is crucial to understand not only the nature of the disruption but also the effects of

the structure of the supply chain and the consequences of choices made by decision makers. Researcher and practitioners should expand their risk analysis to consider the effects of systemic risk and how it influences the ripple effect.

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